THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

DOI

http://dx.doi.org/10.5670/oceanog.2012.37

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2012**	2. REPORT TYPE	3. DATES COVERED **00-00-2012 to 00-00-2012**

4. TITLE AND SUBTITLE **An Introduction To The Special Issue On Internal Waves**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Office of Naval Research,875 North Randolph Street ,Arlington,VA,22217**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Oceanography, Volume 25, Number 2, 2012, 1/20

14. ABSTRACT
This special issue of Oceanography presents a survey of recent work on internal waves in the ocean. The undersea analogue to the surface waves we see breaking on beaches, internal waves play an important role in transferring heat energy, and momentum in the ocean. When they break, the turbulence they produce is a vital aspect of the ocean?s meridional overturning circulation. Numerical circulation models must parameterize internal waves and their breaking because computers will likely never be powerful enough to simultaneously resolve climate and internal wave scales.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

AN INTRODUCTION TO THE SPECIAL ISSUE ON INTERNAL WAVES

BY LOUIS ST. LAURENT, MATTHEW H. ALFORD, AND TERRI PALUSZKIEWICZ

This special issue of *Oceanography* presents a survey of recent work on internal waves in the ocean. The undersea analogue to the surface waves we see breaking on beaches, internal waves play an important role in transferring heat, energy, and momentum in the ocean. When they break, the turbulence they produce is a vital aspect of the ocean's meridional overturning circulation. Numerical circulation models must parameterize internal waves and their breaking because computers will likely never be powerful enough to simultaneously resolve climate and internal wave scales. The demonstrated sensitivity of these models to the magnitude and distribution of internal wave-driven mixing is the primary motivation for the study of oceanic internal waves. Because internal waves can travel far from their source regions to where they break, progress requires understanding not only their generation but also their propagation through the eddying ocean and the processes that eventually lead to their breaking. Additionally, in certain regions such as near coasts and near strong generation regions, internal waves can develop into sharp fronts wherein the thermocline dramatically shoals hundreds of meters in only a few minutes. These "nonlinear" internal waves can have horizontal currents of several knots (1 knot is roughly 2 meters per second), and are strong enough to significantly affect surface navigation of vessels. Vertical current anomalies often reach one knot as well, posing issues for subsurface navigation and engineering structures associated with offshore energy development. Finally, the upwelling and turbulent mixing supported by internal waves can be vital for transporting nutrient-rich fluid into coastal ecosystems such as coral reefs. Below, we provide a very brief introduction to some of the central concepts discussed in the 14 articles that make up the special issue section, and then put each of these articles in context.

A BRIEF TUTORIAL ON INTERNAL WAVES

Internal waves exist in any fluid supporting stratification. In the case of the ocean, stratification involves layers of warm and/or fresh water overlying either cool and/or salty water. Perturbations cause the fluid to move up or down, and these perturbations encounter a restoring buoyancy force, with wave motion resulting. The waves radiate phase (the pattern of crests and troughs) and energy horizontally, and also vertically (unlike surface waves, which are constrained to the interface between water and air), perpendicular to one another. They also disperse, meaning that waves of different scales and frequencies propagate at different rates. These rich characteristics make internal waves a favorite topic of dynamists in nearly all fields of fluid studies.

For the ocean, the topic is still a

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primary area of study, and will continue to be for the foreseeable future. In the grand scheme of energy flow in the ocean, the motions forced by winds, tides, and convection (heating and cooling) trigger a cascade from large scales to small. There are two key waypoints in this cascade: the mesoscale and the overturning scale. The mesoscale is the scale of ocean eddies. Named the Rossby deformation radius (Pedlosky, 1987), this $O(10^5)$ m is the scale where the effects of rotation balance pressure forces, creating geostrophic balance. The overturning scale is the scale of internal wave instability. Named the Ozmidov Scale (Thorpe, 2007), this $O(10^0)$ m scale is where buoyancy forces balance the inertia of turbulent vortices. The internal wave continuum in the ocean's interior serves a nearly exclusive role in bridging the gap between these scales. The internal wave field is always close to instability on the 1 to 10 m scales associated with turbulence. The exchange of energy between these scales, which leads to turbulent mixing, has long been a subject of study (e.g., Gregg, 1987). Once energy is transferred to the overturning scale, it moves through the final segment of the cascade via turbulent processes that lead to the dissipative scale where viscosity transforms kinetic energy into molecular heat.

The cascade at larger scales is still poorly understood. The internal wave energy spectrum is generally "red," with most energy at larger scales whose horizontal wavelengths are between 10 and 100 km. The internal wave field at these scales is described by low-numbered modal solutions (i.e., long vertical wavelengths) of the shallow-water equations (Gill, 1982); hence, such wave scales are called "low modes." Low modes are generally very stable and tend to radiate over O(1,000) km distances. High modes, on the other hand, represent the finer scales of the internal wave continuum, and are subject to instability. A considerable succession of internal wave processes must be implicated to cascade low-mode energy to scales where instability can produce turbulence.

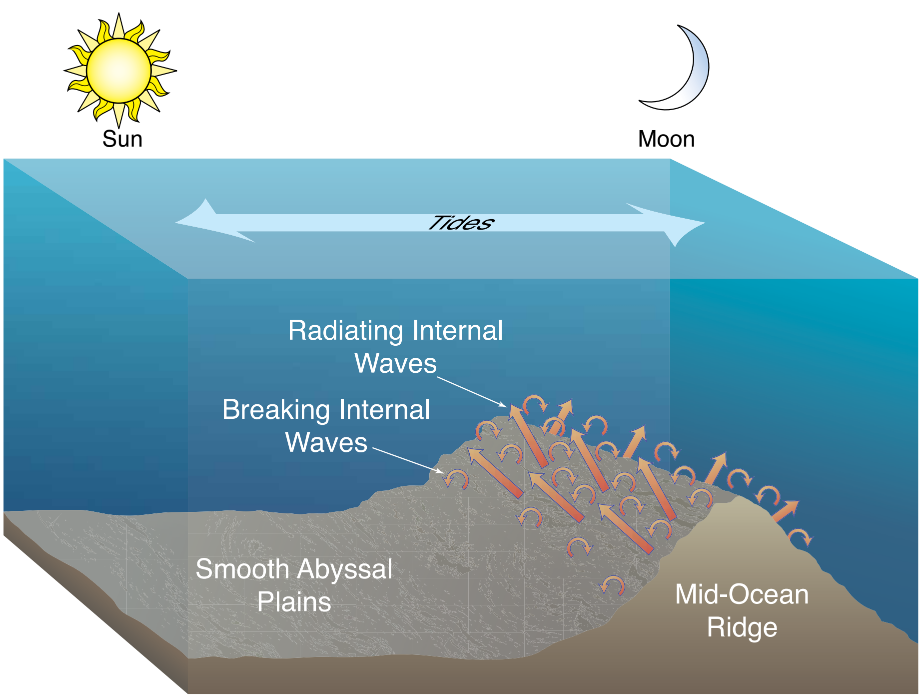

Figure 1. Cartoon depicting the generation of internal tides at a mid-ocean ridge location in the abyssal ocean. Few waves are generated over the smooth abyssal plains, while over a mid-ocean ridge, internal waves are generated by the tides flowing over rough topography. Most of the waves radiate away from the ridge, but some break up into turbulence near the ridge and cause turbulent mixing. *Figure from Jayne et al. (2004)*

The advent of global-scale sea surface altimetry resulted in renewed interest in tides in general, and internal tides have been the focus of much attention in recent years. Numerical methods for assimilating tidal data (Egbert and Erofeeva, 2002) provided the necessary tool for global-scale prediction of open-ocean tides. The Sun and the Moon give rise to a barotropic tide, a wave response driven by a pressure anomaly caused by changes in sea surface elevation. The term *barotropic* signifies that the pressure anomaly is transmitted equally from the sea surface to the seafloor, representing a body force acting on the ocean. The barotropic tides, acting on the combination of density stratification and seafloor topography, give rise to a *baroclinic* response, one that allows pressure anomalies to transmit across density surfaces. This baroclinic response gives rise to internal tides—the internal wave family whose frequencies are those of the tides (Figure 1).

Using an inversion of sea surface altimetry data, Egbert and Ray (2000) provided the first large-scale estimates of internal tide energy levels throughout the world ocean (Figure 2a). They found that roughly 1 TW (10^{12} Watts)

of barotropic tidal power is input into the internal tides. Their map continues to be influential in guiding research into areas where internal tides are enhanced. Global-scale, forward models (running forward in the time-dependent equations, in contrast to inverse methods) have also been developed to examine internal tide energy on the global scale (Jayne and St. Laurent, 2001; Arbic et al., 2004; Simmons et al., 2004).

Wind energy also generates internal waves in the ocean. The winds force only the near-surface layer directly, which is typically not stratified, and therefore does not support internal waves. The near-surface layer is essentially resonant at the inertial frequency (the local Coriolis frequency, f), and the resulting oscillations generally leak energy into the stratified layer below, generating waves. However, only internal waves with frequencies slightly greater than f can actually radiate. Thus, waves with frequencies near, but slightly greater than, the inertial frequency give rise to the *near-inertial* band of internal waves. Studies using slab model representations of the near-surface layer have been used to predict the winds' energy input into the near-inertial internal wave band (Alford 2001, 2003a; Plueddemann and Farrar, 2006). These studies give estimates of 0.3 TW to 1.3 TW for inertial energy input to the global ocean. Alford's (2003a) estimate from the slab model stands at 0.5 TW (Figure 2b), but the accuracy of these types of calculations and the ultimate fate of the energy remain uncertain.

A seminal description of the oceanic internal wave spectrum was first proposed by Garrett and Munk (1972), and, despite some revisions (Munk, 1981), it remains a fundamental pillar of ocean physics. The waves of the general internal-wave continuum are often depicted as *linear* in dynamical description. Effectively, linearity means that wave amplitudes remain small compared to their wavelengths, and that fluid velocities remain small compared to their phase speeds. But it has long been known that nonlinearity is a fundamental aspect of ocean internal waves (e.g., McComas and Bretherton 1977; Müller et al., 1986). The effects of nonlinearity are often described in terms of spectral transfer of energy (Munk, 1981), with the general result of moving internal wave energy from large wavelengths to small, where turbulence processes act to dissipate energy.

In some special cases, nonlinearity leads to distinct waveforms of steep, rapidly propagating anomalies. These anomalies often develop in the upper ocean, where strong density stratification leads to steps in buoyancy or, in some cases, a sharp interface between layers of differing buoyancy. The anomalies can be either elevations (upward deflections of the density interface) or depressions (downward deflections of the density interface) in nature, and examples of both are ubiquitous. Examples of nonlinear internal waves from the South China Sea were featured in the December 2011 *Oceanography* issue on the Oceanography of Taiwan (Figure 3;

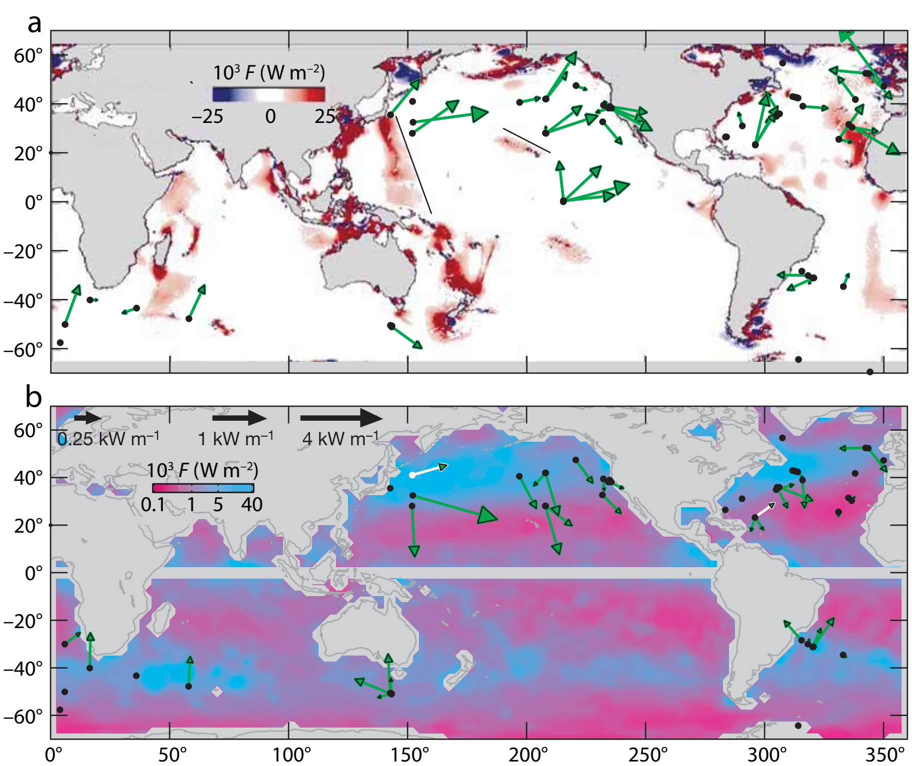

Figure 2. Maps showing energy input into internal waves by (a) semidiurnal tides, and (b) winds. (a) The semidiurnal internal tide energy input was estimated using the TOPEX Poseidon Global Inverse Solution tidal assimilation model (Egbert and Ray, 2000). (b) Annual-mean wind energy input to near-inertial mixed-layer motions as estimated by the model of Alford (2003a). Both panels show vectors of energy flux as measured by mooring records at various sites in the global ocean. Alford (2003b) provides additional details of these maps. *Figure adapted from Alford (2003b)*

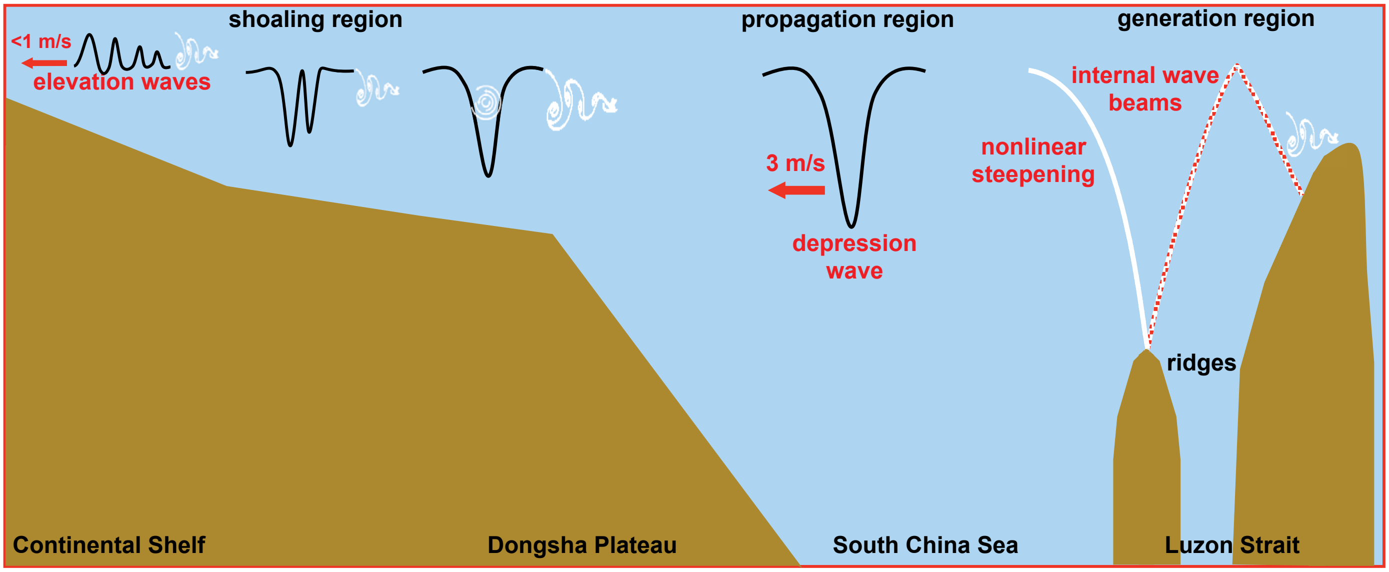

Figure 3. Cartoon depicting nonlinear internal waves in the South China Sea. These internal waves are generated in the Luzon Passage along the double-ridge system. Internal waves then radiate into the South China Sea, where they steepen into soliton-like depression waves. These waves shoal along Dongsha Plateau where they evolve to trains of waves, eventually transforming from depression to elevation waves as they shoal onto the continental shelf. *Figure from St. Laurent et al. (2011)*

http://www.tos.org/oceanography/archive/24-4.html).

A particularly famous special class of nonlinear wave is termed *soliton*, as the anomaly is characterized by a singular pulse (Apel, 2003). More generally, the term solitons, or *solitary waves*, is used to describe any train of steep anomalies whose steep peaks or troughs travel in a coherent group. In some cases, soliton-like internal waves occurring in the upper ocean can influence surface wave properties, leading to patterns of surface roughness visible from ship decks, aircraft, and satellites. Images made using synthetic aperture radar, which can penetrate clouds, are particularly effective at revealing the presence of nonlinear internal waves (see cover image of this issue of *Oceanography*). Chris Jackson of Global Ocean Associates compiled an atlas showing many examples of surface manifestations of soliton-like internal waves (http://www.internalwaveatlas.com).

This brief introduction is intended to whet a reader's appetite for the excellent collection of articles that follow. For more background material on oceanic internal waves, a great many texts now available cover the topic extensively, ranging from introductory (Cushman-Roisin and Beckers, 2011) to advanced (Sutherland, 2010) treatments.

SPECIAL ISSUE ARTICLES

The first several articles in this special issue of *Oceanography* are global-scale presentations of internal waves. *Arbic et al.* and *Simmons and Alford* discuss global simulations of tidal and wind-forced internal wave fields. These studies represent the state of the art in global-scale modeling of internal waves. *Zhao et al.* describe the mapping of large-scale patterns of internal tides with the use of satellite altimetry data.

The next six articles discuss regional and coastal-scale internal waves. *Jachec* and *Carter et al.* present modeling studies of regional-scale internal tides. *Alford et al.* and *Nash et al.* present observations of coastal internal tides. *Da Silva et al.* and *Jackson et al.* present observations of nonlinear internal waves.

Finally, the issue concludes with five papers that describe lee wave, instability, and breaking processes occurring at the smallest scales of the internal wave continuum. *Pinkel et al.* and *Klymak et al.* describe the role of lee waves in internal wave breaking processes. *Smyth and Moum* describe the Kelvin-Helmholtz instability process and the turbulent mixing that it causes. Finally, *Venayagamoorthy and Fringer* and *van Haren and Gostiaux* present studies of breaking internal waves along sloping bottom topography.

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